Gravitational Lensing of Supernovae

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One of the major discoveries of the last decade is that the expansion of the universe appears to be accelerating. This has had profound effects on general relativity, astrophysics, and cosmology, as well as particle physics, and our attempts to find a fundamental theory of everything. There is a growing consensus that understanding the nature of the "dark energy" causing this cosmological acceleration could become one of the defining challenges to fundamental physics for the foreseeable future. A crucial tool in our study of the dark energy is the Type Ia supernova. Because it is an excellent standard candle (object of known intrinsic brightness), it can be used as a precise cosmological distance measure. Supernovae thus allow for the observation of the cosmological distance-redshift relation, and hence the determination of the evolution history of the universe. Gravitational lensing is a major source of noise for these measurements and will need to be thoroughly understood for future ground and space-based supernova surveys to be successful.

Despite what we have all been taught, the universe is *not* described by the Robertson-Walker metric of general relativity. Although this metric works extraordinarily well on the largest scales, it makes the critical (and wrong) assumption that the universe is homogeneous and isotropic. The universe we live in is exceedingly lumpy: galaxies, stars, and planets all represent tremendous overdensities of matter, compared to the background average density of the universe. The gravity from these overdensities causes light from distant sources to bend: gravitational lensing. Since essentially all of astrophysics and cosmology is based upon the observation of photons, all of which pass through our lumpy universe, understanding the impact of gravitational lensing is crucial to correctly interpreting all high-redshift observations. Robert Wald and the author have developed a formalism to calculate lensing statistics in inhomogeneous universes, based upon a careful analysis of the assumptions needed for a physically reasonable model of a globally Robertson-Walker, but locally grossly inhomogeneous universe [1]. The important qualitative features of the magnification distributions can be summarized: any source in an inhomogeneous universe is seen significantly brightened by a few "observers," while the remaining vast majority of observers see the source slightly dimmed (to conserve photon number).

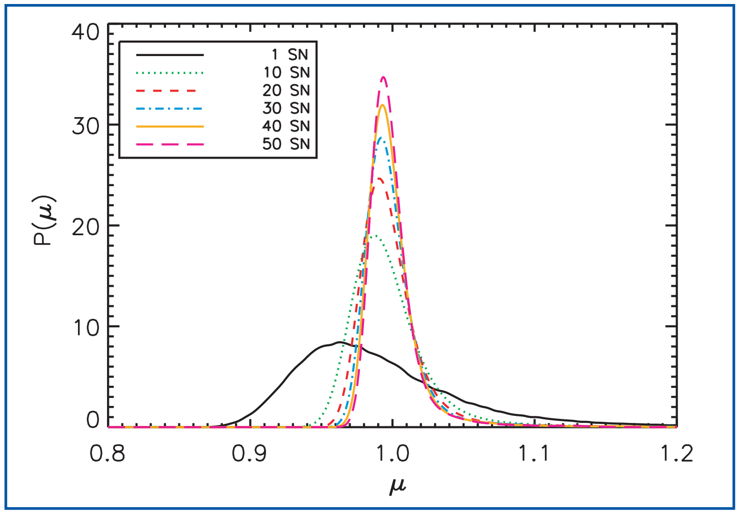
Because the distance-redshift relation is our most direct and promising probe of the dark energy, there has been an explosion of observational interest in high-redshift supernovae (e.g. ACS/GOODS, SNAP, LSST). The "noise" due to lensing lies just beneath the current estimates of supernova intrinsic noise. As our understanding of the supernovae improves (from ground-based, nearby surveys, as well as from future high-redshift data), gravitational lensing could well dominate the error budget. In addition, because the lensing is emphatically non-Gaussian, without a careful and thorough understanding of the effects, the primary analysis and results from these missions could be compromised [2].

One might hope to account for the lensing of supernovae on a case-by-case basis. In [3] we showed that weak-lensing shear maps are unable to correct for weak-lensing magnification: the intrinsic ellipticity of background galaxies is too great, even at the high number density to be expected from the fields of a mission such as SNAP or LSST. In other words, the resolution of the very best weak-lensing shear maps (which engender terrific science all on their own) is still too coarse to be useful to correct for lensing magnification effects. An alternative method to account for gravitational lensing would be to directly identify lenses along the line of sight. A careful analysis of this approach is in progress. In the absence of an ability to correct for the lensing individually, one can average away the effects of lensing through sufficient statistics (since lensing conserves total flux). This also allows for study of the lensing population, and a determination of the fraction of dark matter in compact objects [4].

In current work with Eric Linder [5], we are investigating the degree to which gravitational lensing degrades the cosmological measures that underpin a SNAP-like mission, and thereby estimate how many "extra" supernovae are needed to compensate for the lensing. A crucial property of lensing is that it conserves flux: the average magnification due to lensing is the unlensed value. This means that, for sufficient numbers of sources observed at high redshift, the average brightness will tend towards the "true" brightness. In this way, lensing can be overcome by sufficient statistics. In Fig. 1 we show the process by which the distribution of brightnesses of successive numbers of supernovae average to the unlensed brightness. From this, we are able to calculate how many additional supernovae need to be observed at high redshift, to compensate for the lensing effects. This degradation factor is shown in Fig. 2.

Gravitational lensing compromises the use of standard candles at high redshift. Although this lensing cannot be corrected for on a case-by-case basis, it can be overcome through sufficient statistics. For example, by doubling a data set at redshift 1.5, lensing can be controlled to a level below the intrinsic noise of supernovae.

[1] D.E. Holz and R.M. Wald, *Phys. Rev. D* **58**, 063501 (1998).
[2] D.E. Holz, *Astrophys. J. Lett.* **506**, L1 (1998).
[3] N. Dalal, D.E. Holz, X. Chen, and J. Frieman, *Astrophys. J. Lett.* **585**, L11 (2003).



[4] U. Seljak and D.E. Holz, *Astron. Astroph. Lett.* **351**, L10 (1999).
[5] D.E. Holz and E.V. Linder, Los Alamos National Laboratory report LA-UR-04-8604, submitted to *Astrophys. J.*

Figure 1—
The probability distribution of magnification, μ, due to gravitational lensing, at redshift z=1.5. As more supernovae are observed, the distributions converge on a delta-function at the unlensed value.

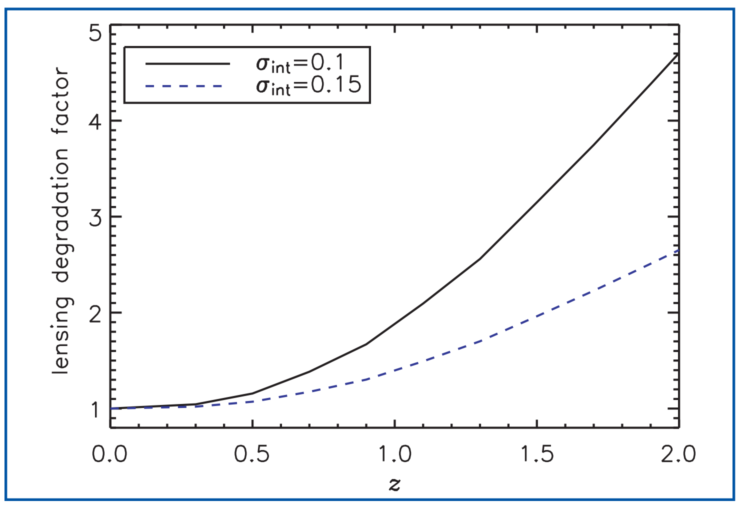


Figure 2—
The lensing degradation factor, as a function of redshift, for supernovae with intrinsic dispersion as shown. At redshift 1.5, at least double the number of supernovae are needed to overcome lensing effects.

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